

EFFECT ON DISPLACEMENT COMPONENTS DUE TO FREE BOUNDARY AND RIGID BOUNDARY IN CASE OF DEFORMATION OF A UNIFORM HALF-SPACE CAUSED BY A VERTICAL TENSILE FAULT

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ABSTRACT: Closed form analytical expressions for the stresses and displacements are derived caused by a long vertical tensile fault buried in a homogeneous, isotropic, perfectly elastic half-space with rigid boundary. The Airy stress function approach has been used to calculate stresses and displacements at an arbitrary point of the half-space. The variation of the displacement field with the horizontal distance from the fault and with the depth is studied numerically and the results obtained in the case of rigid boundary are compared with that of free boundary.

KEY-WORDS: Deformation, Long Tensile Fault, Airy Stress Function, Rigid Boundary.

I. INTRODUCTION

Steketee (1958) and Okada (1985) have applied the theory of dislocation to seismological problems. To understand the deformation or dislocation, the two dimensional models are very useful. Such models are developed by Maruyama (1964), Rybicki (1971), Freund and Barnett (1976) and Davis (1983). In contrast to the progress that has been made in the modeling of the deformation field due to free boundary the studies related to rigid boundary are scarce.

In the present paper, the results of Singh and Garg (1986), Rani et al. (1991) and Singh and Singh (2000) are of direct relevance. These researchers applied the traction-free boundary conditions at the surface of half-space. Malik et al. (2012), Malik et al. (2013) and Malik and Singh (2013) obtained the results by considering the source buried in a half- space with rigid boundary. Following

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the work of above researchers, the airy stress function for a long tensile fault of finite width has been obtained in the present paper and the expressions for stresses and displacements at any point of the half-space with rigid boundary caused by a long vertical tensile fault are derived using the relations between stresses and displacements given by Sokolnikoff (1956). The tensile dislocations are often employed to many seismic events like magma intrusion, dykes injection, mine collapse and study of fluid driven cracks.

II. THEORY

Let the Cartesian coordinates be denoted by (x_1, x_2, x_3) with the x_3 -axis vertically downwards. We consider a two-dimensional approximation in which the displacement components u_1, u_2 and u_3 are independent of x_1 so that $\partial/\partial x_1 \equiv 0$. Under this assumption, the problem reduces to the plain strain case ($u_1 = 0$) that can be solved in terms of the Airy stress function U such that

$$\tau_{22} = \partial^2 U / \partial x_3^2, \tau_{33} = \partial^2 U / \partial x_2^2, \tau_{23} = -\partial^2 U / \partial x_2 \partial x_3 \tag{1}$$

$$\nabla^2 \nabla^2 U = 0 \tag{2}$$

where τ_{ij} are the components of stress and $\nabla^2 \equiv \partial^2/\partial x_2^2 + \partial^2/\partial x_3^2$ ($i, j = 2, 3$)

and

$$2\mu u_2 = -\partial U / \partial x_2 + (1/2\alpha) \int \nabla^2 U dx_2, \tag{3}$$

$$2\mu u_3 = -\partial U / \partial x_3 + (1/2\alpha) \int \nabla^2 U dx_3,$$

where u_i are displacement components and $\alpha = (\lambda + \mu)/(\lambda + 2\mu) = 1/2(1 - \sigma)$.

Here, σ = Poisson's Ratio, μ = Rigidity.

As shown by Singh and Garg (1986), the Airy stress function U_0 for a line source parallel to x_1 -axis passing through the point $(0, 0, h)$ in an infinite medium can be expressed in the form:

$$U_0 = \int_0^\infty [(L_0 + M_0 k |x_3 - h|) \sin kx_2 + (P_0 + Q_0 k |x_3 - h|) \cos kx_2] k^{-1} e^{-k|x_3 - h|} dk \tag{4}$$

where the source coefficients L_0, M_0, P_0 and Q_0 are independent of k .

For a line source parallel to x_1 -axis acting at the point $(0, 0, h)$ of the half-space $x_3 \geq 0$, a suitable solution of biharmonic equation (2) is of the form

$$U = U_0 + \int_0^\infty [(L + Mkx_3) \sin kx_2 + (P + Qkx_3) \cos kx_2] k^{-1} e^{-kx_3} dk \tag{5}$$

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where U_0 is given by equation (4) and L, M, P and Q are unknowns to be determined from the boundary conditions. We assume that the surface of the half-space $x_3 \geq 0$ is with rigid boundary. Therefore the boundary conditions are

$$u_2 = u_3 = 0 \text{ at } x_3 = 0. \tag{6}$$

Using equations (3), (5) and (6), we get (for $\alpha = 2/3$)

$$\left. \begin{aligned} L &= (1/2)[L_0 + (3/2)M_0 + M_0kh]e^{-kh} \\ M &= (1/2)[2L_0 - M_0 + 2M_0kh]e^{-kh} \\ P &= (1/2)[P_0 + (3/2)Q_0 + Q_0kh]e^{-kh} \\ Q &= (1/2)[2P_0 - Q_0 + 2Q_0kh]e^{-kh} \end{aligned} \right\} \tag{7}$$

Putting these values of L, M, P and Q in equation (5) and integrating, we obtain the Airy stress function at any point of the half-space as:

$$\begin{aligned} U &= L_0 \left[\tan^{-1} \left\{ x_2 / (h - x_3) \right\} + (1/2) \tan^{-1} \left\{ x_2 / (x_3 + h) \right\} + x_2 x_3 S^{-2} \right] + M_0 \left[-x_2 (x_3 - h) R^{-2} \right. \\ &\quad \left. + (3/4) \tan^{-1} \left\{ x_2 / (x_3 + h) \right\} - (1/2) x_2 (x_3 - h) S^{-2} + 2x_2 x_3 h (x_3 + h) S^{-4} \right] \\ &\quad + P_0 \left[-\log R - (1/2) \log S + x_3 (x_3 + h) S^{-2} \right] + Q_0 \left[(x_3 - h)^2 R^{-2} - (3/4) \log S - (1/2) (x_3^2 - h^2) S^{-2} \right. \\ &\quad \left. - x_3 h \left\{ x_2^2 - (x_3 + h)^2 \right\} S^{-4} \right] \end{aligned} \tag{8}$$

where $R^2 = x_2^2 + (x_3 - h)^2, S^2 = x_2^2 + (x_3 + h)^2, x_3 \neq h$.

Following Singh and Singh (2000) and using equation (8), the Airy Stress function due to a tensile dislocation on an inclined plane can be expressed in the form

$$\begin{aligned} U &= \left\{ \mu b d s / 2\pi (1 - \sigma) \right\} \left[-\log R - (1/2) \log S + x_3 (x_3 + h) S^{-2} + \sin 2\delta \left\{ -x_2 (x_3 - h) \left[R^{-2} + (1/2) S^{-2} \right] \right. \right. \\ &\quad \left. \left. + 2x_2 x_3 h (x_3 + h) S^{-4} + (3/4) \tan^{-1} \left\{ x_2 / (x_3 + h) \right\} \right\} \right. \\ &\quad \left. + \cos 2\delta \left\{ (x_3 - h)^2 R^{-2} - (1/2) (x_3^2 - h^2) S^{-2} \right. \right. \\ &\quad \left. \left. - x_3 h \left\{ x_2^2 - (x_3 + h)^2 \right\} S^{-4} - (3/4) \log S \right\} \right] \end{aligned} \tag{9}$$

where σ =Poisson's Ratio, μ =Rigidity.

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Equation (9) gives the Airy stress function for a line tensile dislocation located at the point $(0, h)$. If the line source is located at an arbitrary point (y_2, y_3) , then x_2 and h in equation (9) should be replaced by $(x_2 - y_2)$ and y_3 respectively. We obtain

$$\begin{aligned}
 U = \{ \mu b d s / 2\pi (1 - \sigma) \} [& -\log R - (1/2) \log S + x_3 (x_3 + y_3) S^{-2} + \sin 2\delta \{ -(x_2 - y_2)(x_3 - y_3) \{ R^{-2} + (1/2) S^{-2} \} \\
 & + 2(x_2 - y_2)(x_3 + y_3) x_3 y_3 S^{-4} + (3/4) \tan^{-1} \{ (x_2 - y_2) / (x_3 + y_3) \} \} \\
 & + \cos 2\delta \{ (x_3 - y_3)^2 R^{-2} - (1/2) (x_3^2 - y_3^2) S^{-2} - x_3 y_3 \{ (x_2 - y_2)^2 - (x_3 + y_3)^2 \} S^{-4} - (3/4) \log S \}] \quad (10)
 \end{aligned}$$

where

$$R^2 = (x_2 - y_2)^2 + (x_3 - y_3)^2, \quad S^2 = (x_2 - y_2)^2 + (x_3 + y_3)^2.$$

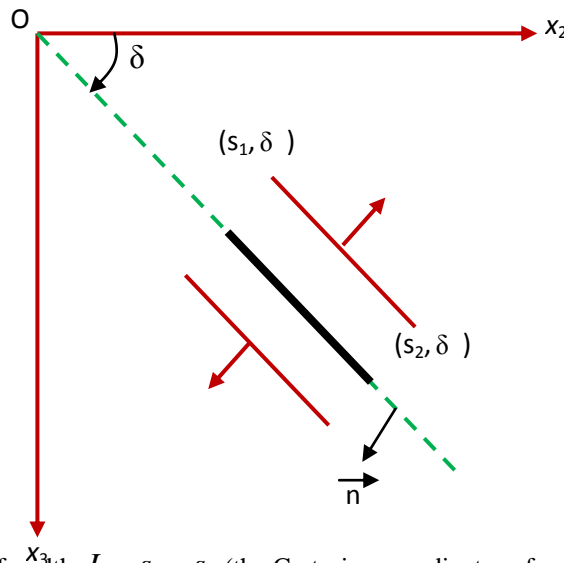


Fig. 1 Geometry of a long tensile fault of width $L = s_2 - s_1$ (the Cartesian coordinates of a point on the fault are (y_2, y_3) and its polar coordinates are (s, δ) , where δ is the dip angle and $s_1 \leq s \leq s_2$)

From Figure 1, we put $y_2 = s \cos \delta, y_3 = s \sin \delta$ into equation (10) and integrate over s between the limits (s_1, s_2) . We obtain the following expression for the airy stress function for a long vertical tensile fault of finite width $L = s_2 - s_1$;

$$U = \{ \mu b / 2\pi (1 - \sigma) \} [(x_3 - s) \log R + (1/4) (5x_3 + s) \log S - (3/4) s$$

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$$-x_3(x_2^2 + x_3^2 + x_3s)S^{-2} + (3/4)x_2 \tan^{-1}\{(x_3 + s)/x_2\} \Big]_{s_1}^{s_2} \tag{11}$$

Using equations (1), (3) and (11), we obtain the following expressions for stress and displacement components for a uniform half-space with rigid boundary due to a vertical tensile fault:

$$\tau_{22} = \{\mu b/2\pi(1-\sigma)\} \left[(x_3 - s)R^{-2} + (1/4)(5x_3 + s)S^{-2} + 2x_2^2(x_3 - s)R^{-4} - 8x_2^2x_3s(x_3 + s)S^{-6} + (x_2^2x_3 + 3x_2^2s + 2x_3^2s + 2x_3s^2)S^{-4} \right]_{s_1}^{s_2} \tag{12}$$

$$\tau_{23} = \{\mu b/2\pi(1-\sigma)\} \left[x_2\{R^{-2} - (1/4)S^{-2}\} - 2x_2^3R^{-4} - x_2(x_2^2 + 6x_3s)S^{-4} + 8x_2^3x_3sS^{-6} \right]_{s_1}^{s_2} \tag{13}$$

$$\tau_{33} = \{\mu b/2\pi(1-\sigma)\} \left[(x_3 - s)R^{-2} - (1/4)(x_3 + 5s)S^{-2} - 2x_2^2(x_3 - s)R^{-4} + 8x_2^2x_3s(x_3 + s)S^{-6} + (-x_2^2x_3 + x_2^2s - 2x_3^2s - 2x_3s^2)S^{-4} \right]_{s_1}^{s_2} \tag{14}$$

$$u_2 = \{b/4\pi(1-\sigma)\} \left[(1-\sigma)\{2 \tan^{-1}\{x_2/(x_3 - s)\} + \tan^{-1}\{x_2/(x_3 + s)\} - 2x_2sS^{-2}\} - x_2(x_3 - s)\{R^{-2} + (1/2)S^{-2}\} + 2x_2x_3s(x_3 + s)S^{-4} - (3/4) \tan^{-1}\{(x_3 + s)/x_2\} \right]_{s_1}^{s_2} \tag{15}$$

$$u_3 = \{b/4\pi(1-\sigma)\} \left[(1-\sigma)\{2 \log R + \log S + 2s(x_3 + s)S^{-2}\} - (3/4) - \log R - (5/4) \log S + x_2^2R^{-2} - (1/2)(x_3^2 + s^2)S^{-2} - 2x_2^2x_3sS^{-4} \right]_{s_1}^{s_2} \tag{16}$$

III. NUMERICAL RESULTS

We compare the displacement fields around a long vertical tensile fault of finite width L in a uniform half-space with rigid boundary with that of free boundary. We put $s_1 = 0$, $s_2 = L$, and assume that $\sigma = 0.25$. For numerical calculations, we define the following dimensionless quantities:

$$Y = x_2/L, \quad Z = x_3/L, \quad P_{ij} = (\pi L/\mu b)\tau_{ij}, \quad U_i = (\pi/b)u_i \tag{17}$$

Thus, Y is the dimensionless distance from the fault; Z is the dimensionless depth; P_{22} , P_{23} and P_{33} are the dimensionless stresses and U_2 and U_3 are the dimensionless displacements.

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From equations (12) to (16) and (17), we obtain

$$P_{22} = (2/3) \left[(Z-1)A^{-2} + (1/4)(5Z+1)B^{-2} + 2Y^2(Z-1)A^{-4} + (Y^2Z + 3Y^2 + 2Z^2 + 2Z)B^{-4} - 8Y^2Z(Z+1)B^{-6} - (3/4)Z(7Y^2 + 3Z^2)C^{-4} \right] \quad (18)$$

$$P_{23} = (2/3) \left[Y \{ A^{-2} - (1/4)B^{-2} \} - 2Y^3A^{-4} - (Y^3 + 6YZ)B^{-4} + 8Y^3ZB^{-6} - (1/4)Y(Y^2 + 3Z^2)C^{-4} \right] \quad (19)$$

$$P_{33} = (2/3) \left[(Z-1)A^{-2} - (1/4)(Z+5)B^{-2} - 2Y^2(Z-1)A^{-4} + (-Y^2Z + Y^2 - 2Z^2 - 2Z)B^{-4} + 8Y^2Z(Z+1)B^{-6} - (3/4)Z(Z^2 - 3Y^2)C^{-4} \right] \quad (20)$$

$$U_2 = (1/3) \left[-Y(Z-1)A^{-2} - (1/2)Y(Z+2)B^{-2} + 2YZ(Z+1)B^{-4} + (3/2)YZC^{-2} + (3/4) \tan^{-1} \left\{ Y^2 - (Z+1)^2 / 2Y(Z+1) \right\} + (3/4) \tan^{-1} \left\{ Z^2 - Y^2 / 2YZ \right\} + (3/2) \tan^{-1} \left\{ Y / (Y^2 + Z^2 - Z) \right\} \right] \quad (21)$$

$$U_3 = (1/3) \left[(1/2) \log(A/B) + (1/2)(2 + 3Z - Z^2)B^{-2} + Y^2A^{-2} - 2Y^2ZB^{-4} + (1/2)(Z^2 - 2Y^2)C^{-2} \right] \quad (22)$$

Following are the expressions for free boundary (Singh and Singh 2000) for the dimensionless stresses and displacements due to a vertical tensile fault:

$$P_{22}^* = (2/3) \left[(Z-1)A^{-2} - (3Z+1)B^{-2} + 2Y^2(Z-1)A^{-4} + 2(Z^3 + Z^2 + Z + 1 - 2Y^2)B^{-4} + 16Y^2Z(Z+1)B^{-6} \right] \quad (23)$$

$$P_{23}^* = (3Y/2) \left[A^{-2} + B^{-2} - 2Y^2A^{-4} - 2(Z^2 - 4Z + 1)B^{-4} - 16Y^2ZB^{-6} \right] \quad (24)$$

$$P_{33}^* = (2/3) \left[(Z-1) \{ A^{-2} - B^{-2} \} - 2Y^2(Z-1) \{ A^{-4} - B^{-4} \} + 4Z(Z+1)B^{-4} - 16Y^2Z(Z+1)B^{-6} \right] \quad (25)$$

$$U_2^* = (1/2) \left[2YB^{-2} + \tan^{-1} \{ Y / (Z-1) \} - \tan^{-1} \{ Y / (Z+1) \} - (2/3)Y(Z-1) \{ A^{-2} - B^{-2} \} - (8/3)YZ(Z+1)B^{-4} \right] \quad (26)$$

$$U_3^* = (1/3) \left[(1/2) \log(A/B) + Y^2A^{-2} + (Z^2 - 3Z - 2)B^{-2} + 4Y^2ZB^{-4} - 1 \right] \quad (27)$$

where

$$A^2 = Y^2 + (Z-1)^2, B^2 = Y^2 + (Z+1)^2, C^2 = Y^2 + Z^2.$$

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IV. DISCUSSION

Figures 2(a)-2(g) show the variation of the dimensionless horizontal displacement U_2 of a uniform half-space with rigid boundary and free boundary respectively with the dimensionless distance from the fault caused by a vertical tensile fault at $x_3 = 0.1L, 0.5L, 0.75L, 1.0L, 1.5L, 1.75L$ and $2.0L$ respectively. The broken lines show the variation when the half-space is with free boundary and the continuous lines represent the half-space with rigid boundary. We notice that the pattern of variation of U_2 changes at $x_3 = L$. It is different for $x_3 < L$ and $x_3 > L$ for both the cases. As x_2 tends to infinity, U_2 converges to zero rapidly for rigid boundary in comparison to that of free boundary.

Figures 3(a)-3(g) show the variation of the dimensionless horizontal displacement U_2 with depth at $x_2 = 0.1L, 0.5L, 0.75L, 1.0L, 1.5L, 1.75L$ and $2.0L$ respectively. The variation of U_2 is smooth for all the values of x_3 in the case of rigid boundary. But for the case of free boundary, U_2 shows sharp changes at $x_3 = L$ and the variation of U_2 is smooth for $x_3 < L$ and $x_3 > L$.

Figures 4(a)-4(g) show the variation of the dimensionless vertical displacement U_3 with dimensionless distance from the fault at $x_3 = 0.1L, 0.5L, 0.75L, 1.0L, 1.5L, 1.75L$ and $2.0L$ respectively. U_3 has positive values for rigid boundary and negative values for free boundary for all the values of x_3 . Finally, U_3 tends to zero as x_2 tends to infinity for both the cases.

Figures 5(a)-5(g) show the variation of the dimensionless vertical displacement U_3 with depth at $x_2 = 0.1L, 0.5L, 0.75L, 1.0L, 1.5L, 1.75L$ and $2.0L$ respectively. We notice that near the fault, the pattern of variation of U_3 is same for both the cases. Finally, as x_2 approaches to infinity, U_3 tends to zero for both free boundary and rigid boundary.

Thus, for all the cases the displacement components U_2 and U_3 converges to zero as x_2 and x_3 tends to infinity respectively for both free boundary and rigid boundary cases.

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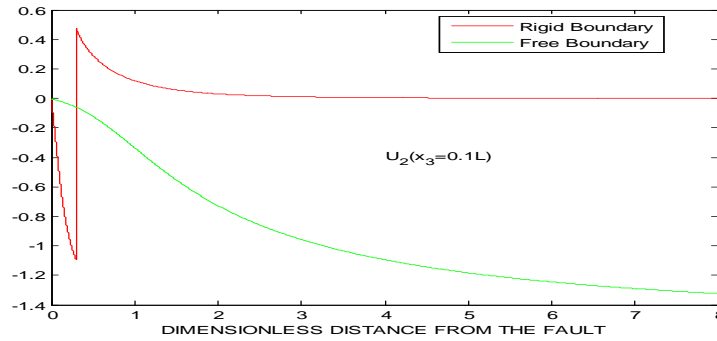


Fig. 2(a) Variation of U_2 with distance from the fault for $x_3=0.1L$

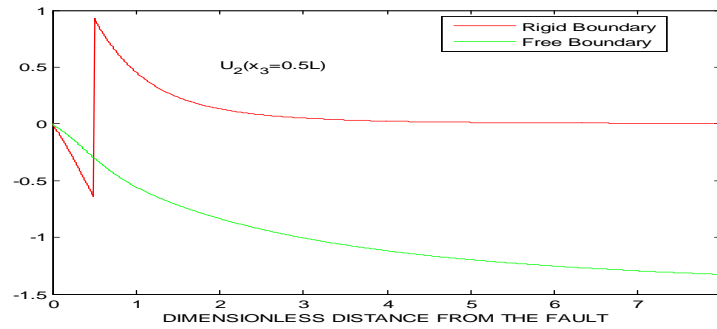


Fig. 2(b) Variation of U_2 with distance from the fault for $x_3=0.5L$

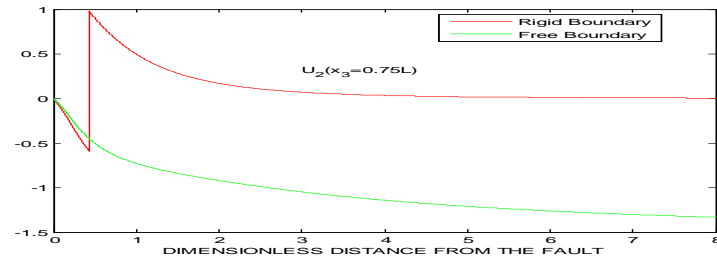


Fig. 2(c) Variation of U_2 with distance from the fault for $x_3=0.75L$

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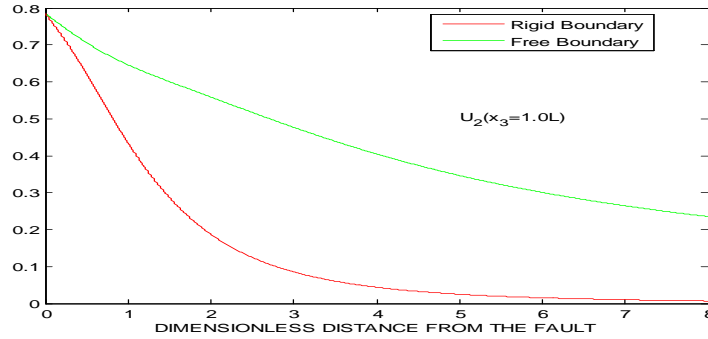


Fig. 2(d) Variation of U_2 with distance from the fault for $x_3=1.0L$

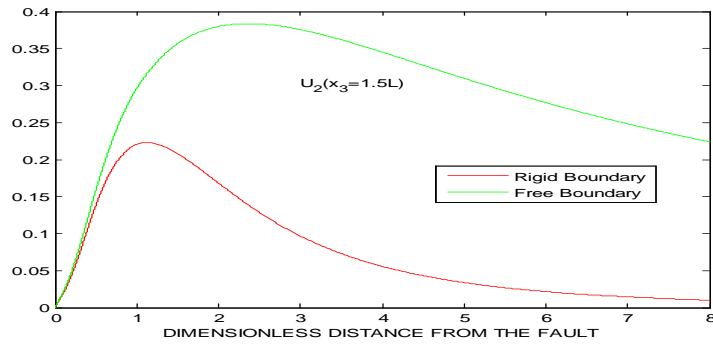


Fig. 2(e) Variation of U_2 with distance from the fault for $x_3=1.5L$

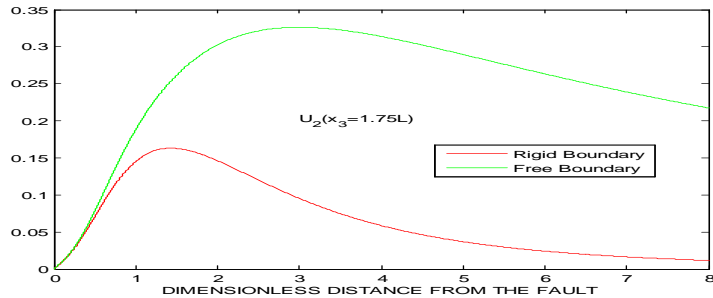


Fig. 2(f) Variation of U_2 with distance from the fault for $x_3=1.75L$

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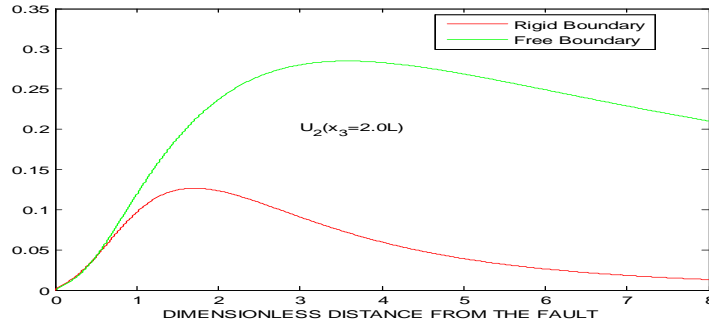


Fig. 2(g) Variation of U_2 with distance from the fault for $x_3=2.0L$

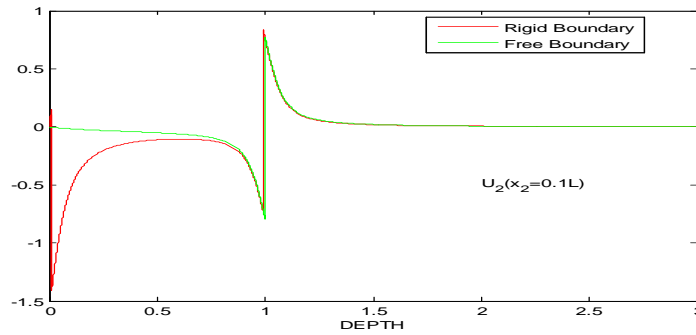


Fig. 3(a) Variation of U_2 with depth from the fault for $x_2=0.1L$

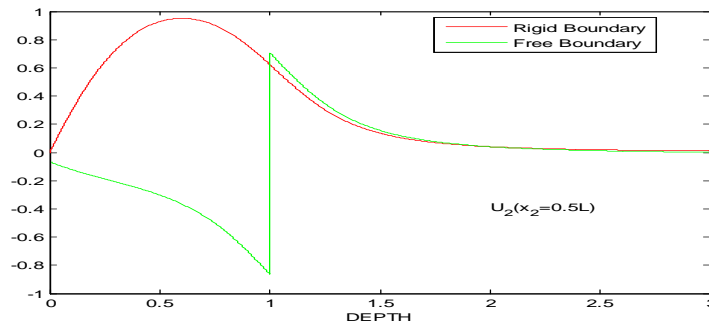


Fig. 3(b) Variation of U_2 with depth from the fault for $x_2=0.5L$

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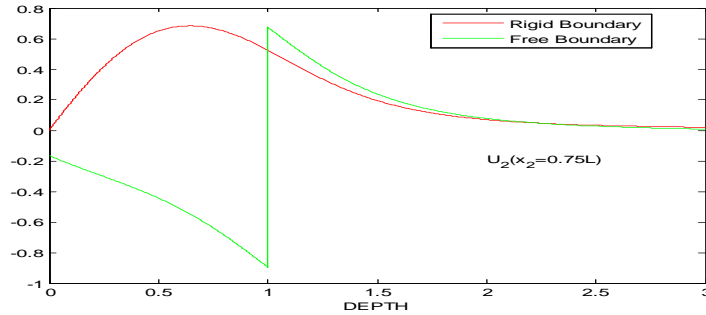


Fig. 3(c) Variation of U_2 with depth from the fault for $x_2=0.75L$

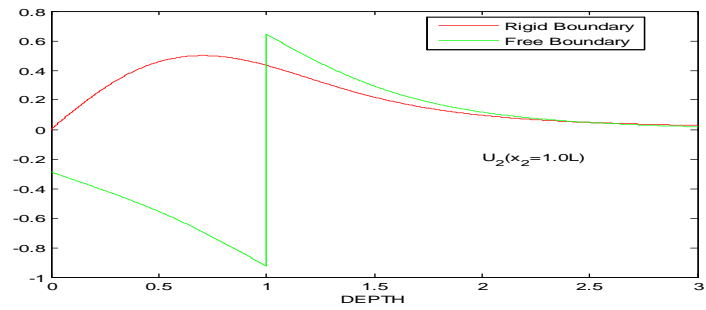


Fig. 3(d) Variation of U_2 with depth from the fault for $x_2=1.0L$

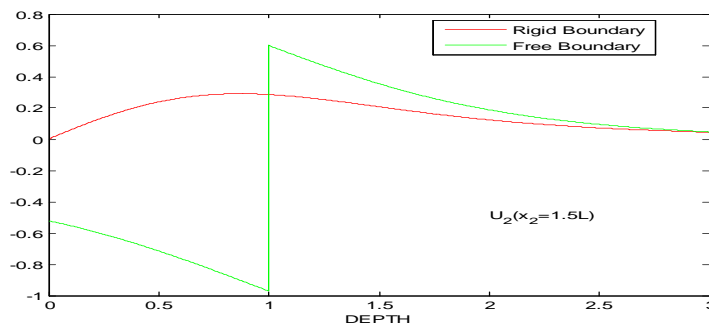


Fig. 3(e) Variation of U_2 with depth from the fault for $x_2=1.5L$

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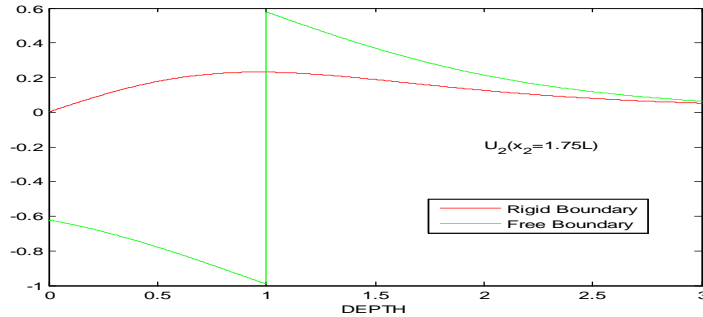


Fig. 3(f) Variation of U_2 with depth from the fault for $x_2=1.75L$

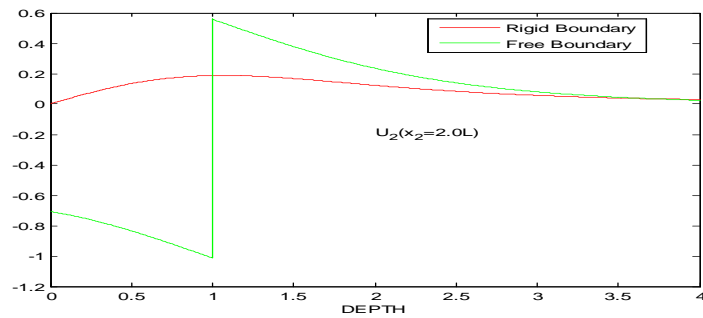


Fig. 3(g) Variation of U_2 with depth from the fault for $x_2=2.0L$

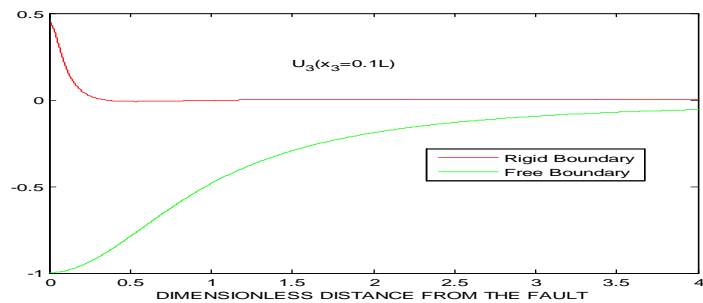


Fig. 4(a) Variation of U_3 with distance from the fault for $x_3=0.1L$

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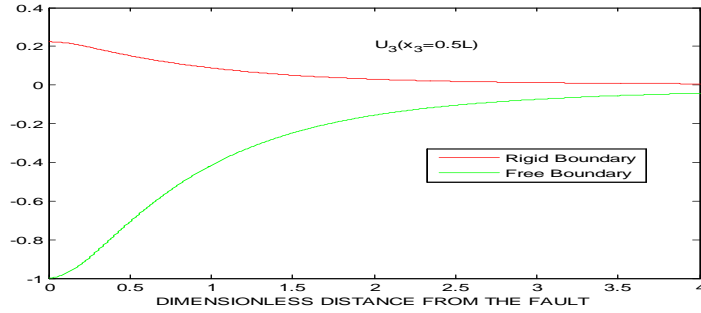


Fig. 4(b) Variation of U_3 with distance from the fault for $x_3=0.5L$

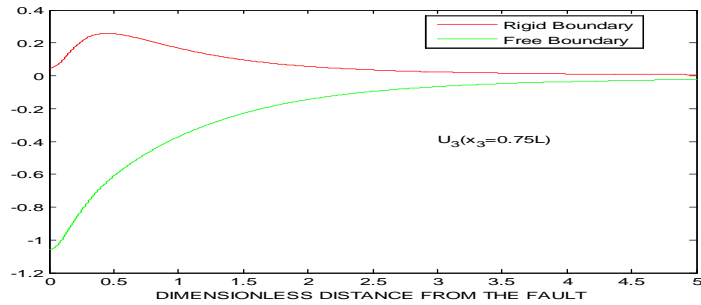


Fig. 4(c) Variation of U_3 with distance from the fault for $x_3=0.75L$

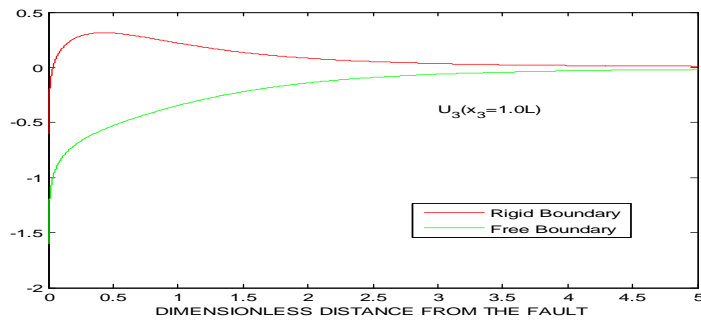


Fig. 4(d) Variation of U_3 with distance from the fault for $x_3=1.0L$

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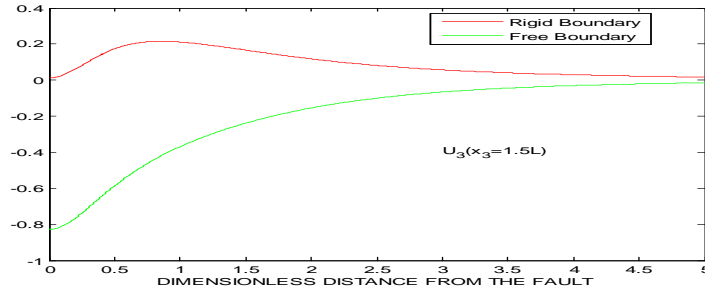


Fig. 4(e) Variation of U_3 with distance from the fault for $x_3 = 1.5L$

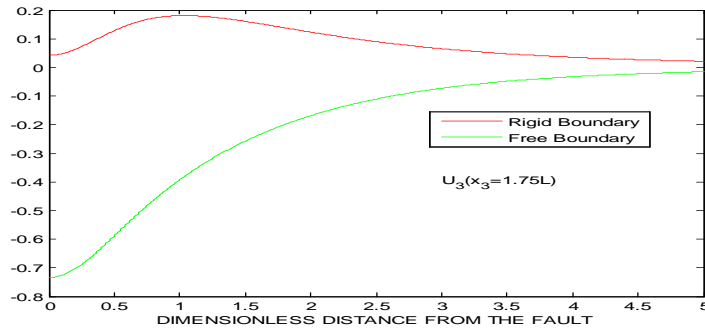


Fig. 4(f) Variation of U_3 with distance from the fault for $x_3 = 1.75L$

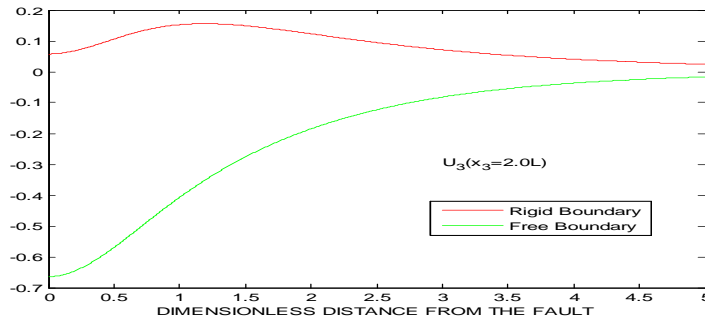


Fig. 4(g) Variation of U_3 with distance from the fault for $x_3 = 2.0L$

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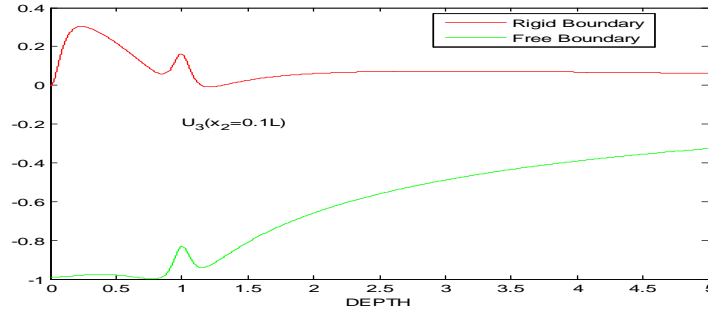


Fig. 5(a) Variation of U_3 with depth from the fault for $x_2=0.1L$

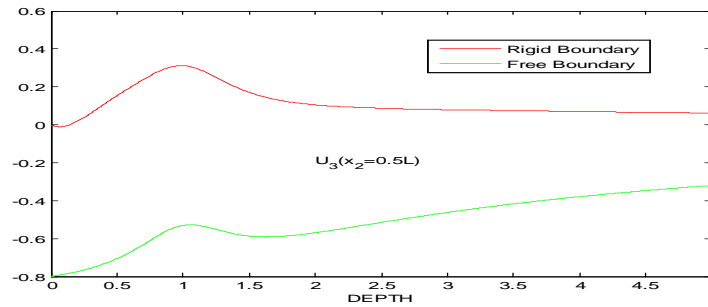


Fig. 5(b) Variation of U_3 with depth from the fault for $x_2=0.5L$

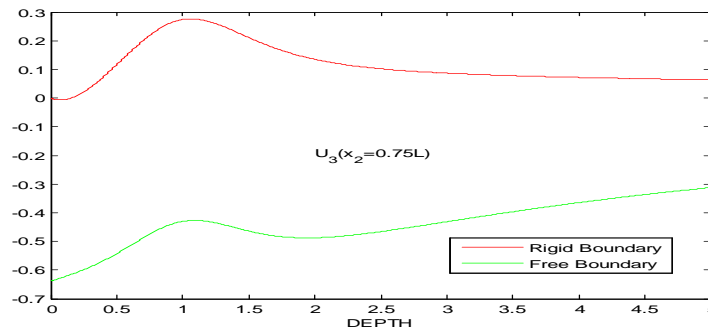


Fig. 5(c) Variation of U_3 with depth from the fault for $x_2=0.75L$

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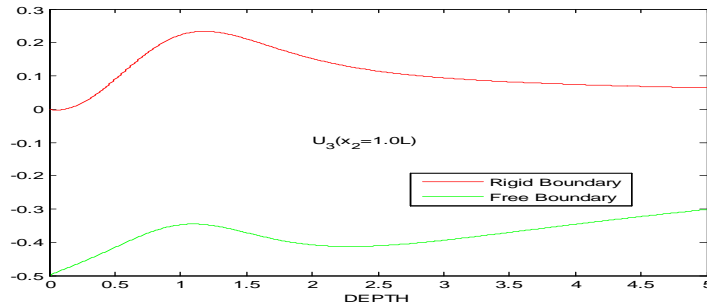


Fig. 5(d) Variation of U₃ with depth from the fault for x₂=1.0L

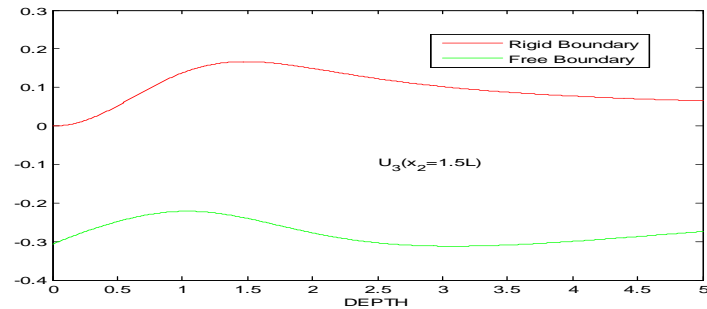


Fig. 5(e) Variation of U₃ with depth from the fault for x₂=1.5L

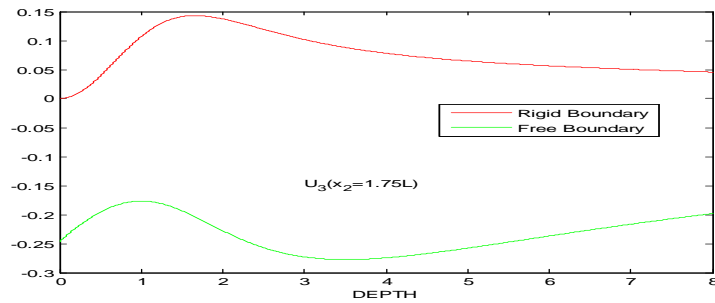


Fig. 5(f) Variation of U₃ with depth from the fault for x₂=1.75L

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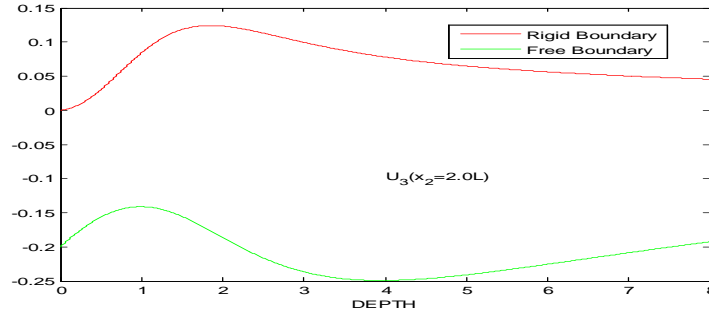


Fig. 5(g) Variation of U_3 with depth from the fault for $x_2=2.0L$

V. CONCLUSION

1. The displacement components U_2 and U_3 have no negative values for almost all values of x_2 and x_3 in case of rigid boundary where as they have mixed sign in case of free boundary.
2. There is a sudden change in the value of U_2 at $x_3=L$ in case of free boundary and similar behaviour appears near origin ($0 < x_2 < L$) in case of rigid boundary.
3. The variation of U_2 and U_3 is smooth for both the cases of free boundary and rigid boundary, when values of x_2 and x_3 are infinitely large.

APPENDIX

1. Vertical dip-slip fault

$$L_0 = P_0 = Q_0 = 0, \quad M_0 = \pm \frac{\mu b d s}{2\pi(1-\sigma)}$$

2. Vertical tensile fault

$$L_0 = M_0 = 0, \quad P_0 = -Q_0 = \frac{\mu b d s}{2\pi(1-\sigma)}$$

3. Horizontal tensile fault

$$L_0 = M_0 = 0, \quad P_0 = Q_0 = \frac{\mu b d s}{2\pi(1-\sigma)}$$

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In case of vertical dip-slip fault, the positive sign is for $x_3 > h$ and the negative sign is for $x_3 < h$, b is the magnitude of the displacement dislocation and ds is the width of the fault.

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